COMPUTERS AND BIOMEDICAL RESEARCH 2, 537–548 (1969)

Electrocardiographic Interpretation by Computer

T. ALLAN PRYOR, RICHARD RUSSELL, ALBERTO BUDKIN, AND
W. GARY PRICE

*Department of Biophysics and Bioengineering
University of Utah
and
Latter-day Saints Hospital,
Salt Lake City, Utah*

Received June 11, 1969

A program for the automatic interpretation of electrocardiograms using a general purpose digital computer has been under development at the Latter-day Saints Hospital. The analysis is performed using the orthogonal *XYZ* Franck lead system. This system was chosen in order to reduce the amount of data transmitted and analyzed by the computer. Interpretive statements are made concerning only the QRS and ST-T waves of the electrocardiogram at this time. Development is under way for interpretation of the P wave as well as arrhythmia diagnosis.

INTRODUCTION

Since 1964 a program for the automatic interpretation of electrocardiograms using a general purpose digital computer has been under development at Latter-day Saints Hospital. During this time several methods have been studied in order to determine which would result in the optimum interpretation. These methods have included the use of predictive filters, three dimensional histograms and linear discriminate functions. In each case partial success was achieved, but not at the level desired. The present method closely correlates with the interpretation as performed by the cardiologist. The analysis is performed using the orthogonal *XYZ* Franck lead system.[1] This system was chosen in order to reduce the amount of data transmitted and analyzed by the computer. Interpretive statements are made concerning only the QRS and ST—T waves of the electrocardiogram at this time. Development is under way for interpretation of the P wave as well as arrhythmia diagnosis.

There are 11 categories in the QRS interpretation. These are normal, left bundle branch block, right bundle branch block, intraventricular conduction defect, left ventricular hypertrophy, right ventricular hypertrophy, anterior myocardial infarction, inferior myocardial infarction, lateral wall myocardial infarction, left axis deviation and right axis deviation. There are five categories in which the ST and T waves are classified. They are normal, injury pattern, sub-endocardial injury pattern, ischemia pattern, or digitalis effect pattern.

This program is being run routinely on all elective admissions to the hospital. These patients, as they enter the hospital, are taken to a screening area where an electrocardiographic interpretation and other tests are performed. The ECG program can also be used on requested electrocardiograms taken within the L.D.S. Hospital and at remote hospitals.

Figure 1 shows a block diagram of the data collection and reporting system. The patient is connected to a Marquette 3 channel ECG recorder.* This recorder can record the 12 standard electrocardiographic leads on graph paper as well as the vector *XYZ* leads. A telephone data set is attached to the Marquette equipment which transmits the signal over telephone lines to the computer. Once these leads are attached to the patient the operator connects to the computer by using a dial up telephone. After connection to the computer is established, further communication with the computer is accomplished by pressing digits on a keyboard located on the Marquette equipment. Messages are displayed on the Textronics display terminal (if the operator is in the screening area) or on the TV set in the patient's room. The TV display is generated by focusing a TV camera on the face of a memory oscilloscope at the control computer facility. The signal is then fed through a closed circuit system throughout the hospital. By dialing the appropriate channel in the patient's room, the operator is able to view the computer messages.

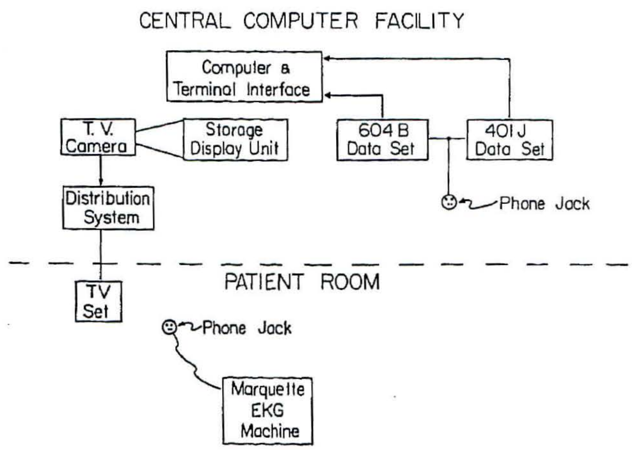


FIG. 1. Shows a block diagram of the system which permits transmission of electrocardiographic information in a form of three vector leads over a telephone connection in the patient's room to the computer and the transmission of instructions and answers from the computer to the patient's room using the standard commercial television set. This is transmitted over Channel 6 within the hospital.

* Marquette Electronics, Milwaukee, Wisconsin.

The operator presses a special button causing the program to be called into the computer and made ready for analysis. Upon receipt of the appropriate message she enters the patient number. After entering the number she positions the switch on the electrocardiographic cart to "ECG". At this time the Marquette equipment will begin recording leads 1, 2 and 3, of the standard 12 leads. After 5 sec. the three channels are switched automatically to standard leads, AVR, AVL and AVF. Following another 5 sec. leads V1, V2, V3 are recorded followed by leads V4, V5 and V6. Finally the equipment will switch to leads *X*, *Y*, *and Z*. These leads are recorded for 20 sec.

During this recording the computer samples the output of the Marquette equipment. Following the 20 sec. of the *XYZ* leads a 1 mV callibration is transmitted on each of the three channels. At the central computer facility the telephone signal is received by the receiving data set and the three leads are reconstituted and fed into a Control Data 3300 Computer System. Once the analysis has been completed by the computer, which takes approximately 1 sec. after all the data has been received, the results are immediately displayed back to the operator. The operator is now able to determine whether the analysis has been technically correct or incorrect. This decision is based on two factors. One is the calibration values which are displayed back and the second is a graph of the waveforms analyzed. If the calibrations are not within predetermined limits the procedure should be repeated. Since under normal circumstances five complexes are analyzed, the technician can view the oscilloscope to determine how many complexes are actually used in the analysis. If less than three complexes are displayed at this time the operator should then repeat the procedure before storing the final interpretation on the patient's record. Once the technician has satisfied herself that the results are technically correct, she presses the interrupt button again to indicate to the computer that the results are satisfactory and cause this information to be stored on the patient's file.

The program allows other *XYZ* recorders to be used by the system other than the Marquette equipment. There are two hospitals in the area using Hewlett Packard Vector Cardiograph equipment* and Bell System data Sets to communicate to the program. Under these circumstances the program determines, based on the source of the data, which type of equipment is involved. Slight variations in the program, the major one being magnitude of the calibration signal, is made depending on the type of sending equipment in each case.

THE PROGRAM

The program itself is divided into two main parts. Part 1 is the data collection and pattern recognition portion. Part 2 extracts the parameters from the electrocardiogram and executes the logic to determine the classification.

* Hewlett Packard, North Hollywood, California.

The first step in collecting the data is to measure the patient's heart rate. This is done by sampling one of the leads for approximately 2 sec. As the data is read into the computer it is searched for a maximum difference over two successive points. This maximum difference is assumed to be at some point on a QRS complex. A tolerance limit is set at ¾ of the value. Two successive QRS complexes are recognized by comparing the difference between points of the incoming data against the tolerance value. The interval between the two complexes is used as the heart rate. The data on all three channels is now sampled in a circular array of 150 samples at the rate of 200 samples per second. That is, as soon as 150 samples are input the counters are reset and new data is stored on top of the old. This allows for 50 samples or .25 sec. for each lead. Upon detection of a difference which is greater than the threshold which had been set, the program will sample 224 points on each of the three leads. This will put in memory approximately 1.30 sec. of electrocardiographic data on each of the three leads. Also, due to the manner of data collection using the threshold to determine when to sample there will be approximately .25 sec. of data before the onset of a QRS and approximately .90 sec. of data following the QRS complex. This insures that at least the onset of two QRS complexes are in core for all patients whose heart rate is greater than about 54 beats per minute. It is necessary to have the onset of two QRS complexes included in order to adjust for base line drift. This set is then stored temporarily on a magnetic disc and the program begins searching for another QRS complex.

After five such sets of data are recorded and stored out on disc the program stops sampling and waits for the calibration signal. Upon receiving an interrupt indicating that the calibration signal is now being transmitted, the program will sample the calibration on each of the three channels in order to determine the deflection due to a calibrated 1 mV signal. This then will be used as the slope in subsequent calibration equations on the data. The calibration values are displayed back to the technician and if she verifies their accuracy she will then interrupt the computer causing the analysis to continue. At this point each of the five sets of data are brought sequentially into the computer and the pattern recognition is performed in order to identify the onset and end of a QRS wave. This is done by finding a maximum difference over three points from each of the three leads and setting a tolerance limit on each lead equal to ⅙ of the maximum difference for that lead. The data is scanned starting from the point where the maximum difference occurred. Once the difference falls below its tolerance for five successive points on all leads the point is flagged as the onset or end of the QRS depending on whether the scan was forward or backward from the point of maximum difference. If due to noise either the start or end is unable to be detected, the set is discarded and a new set read into core and the analysis begun on this set. After this has been done the isolectric point is arbitrarily set to the value of those points just preceding the onset of the QRS. This is found for both the first and

TABLE 1

QRS PARAMETERS

1. QRS duration.
2. Integral in Z over first .04 *sec.* after onset of *QRS*.
3. S wave in X.
4. R' in lead Z.
5. S/R in lead Z.
6. S in lead Z.
7. R/S in lead "V_4".
8. Integral in lead Y over first .04 sec. after onset of QRS.
9. Integral in lead X over first .04 sec. after onset of QRS.
10. S in lead Z.
11. R in lead X.
12. S/R in lead Z.
13. R/S in lead X.
14. R in lead Y.
15. S in lead Y.
16. R in lead X.
17. S in lead X.

second QRS in a set of data and a linear interpolation between these two points is used to find the zero values for calibrating the data. No effort is made to determine the end of the T wave. The calibration, however, is performed on sufficient points, based on the heart rate, to insure that the T wave is included. The calibrated QRS ST–T wave forms are stored temporarily on disc and the analysis part of the program is now read into memory.

Table 1 shows a list of the parameters used in classifying the QRS wave. The parameters are grouped according to their use in the interpretation of the waveform. For example, Group 1 consisting of the QRS duration, the integral in lead Z over the first .04 sec., the presence of an S wave in lead X and an R' in lead Z is used to determine whether the electrocardiogram has a conduction defect, and if so, what type. This will be further explained below. Table 2 shows the para-

TABLE 2

ST-T PARAMETERS

1. ST voltage in lead X.
2. ST voltage in lead Y.
3. ST voltage in lead Z.
4. Curvature in lead X.
5. Curvature in lead Y.
6. Curvature in lead Z.
7. T wave voltage in X.
8. T wave voltage in Y.
9. T wave voltage in Z.

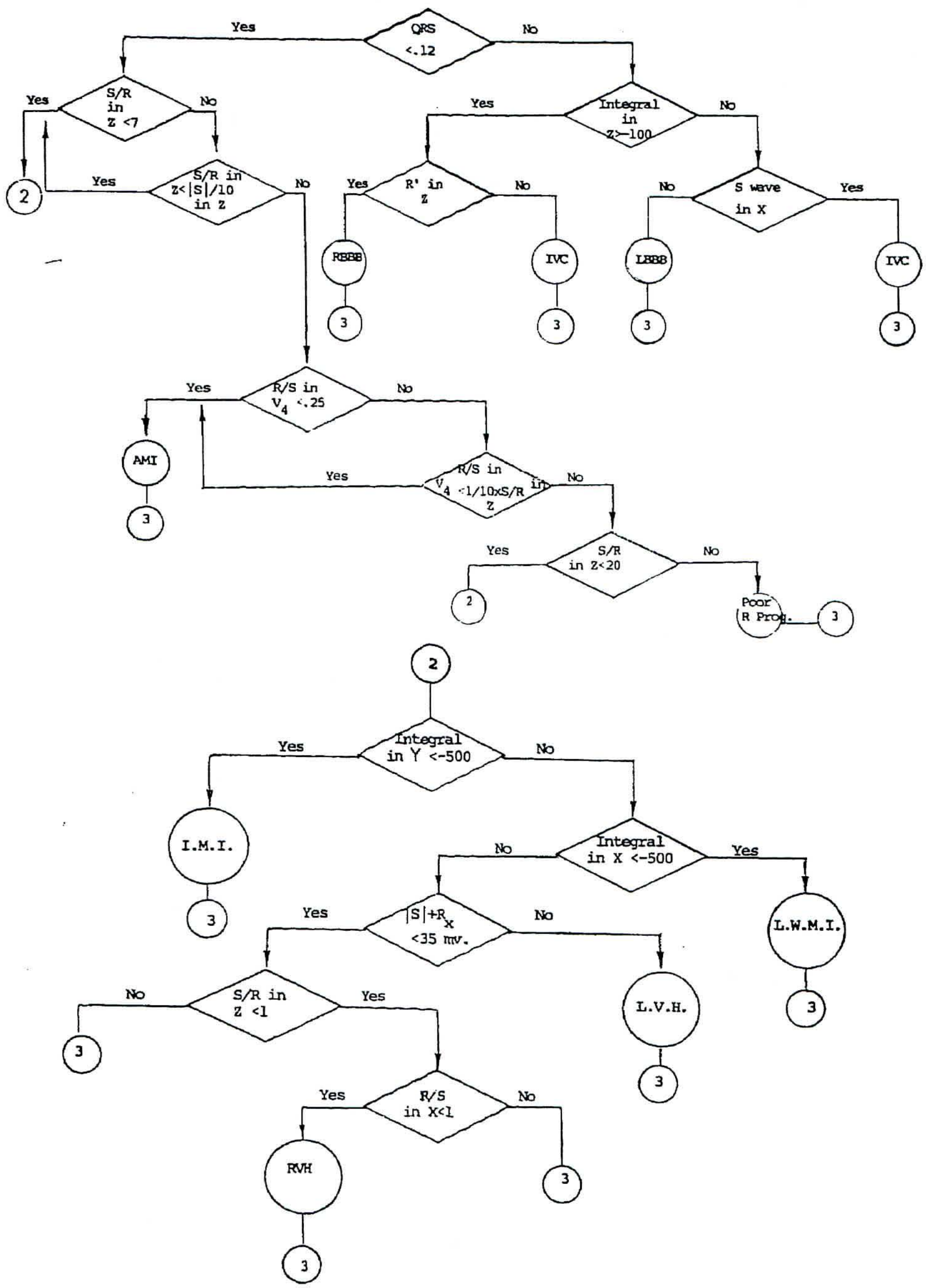
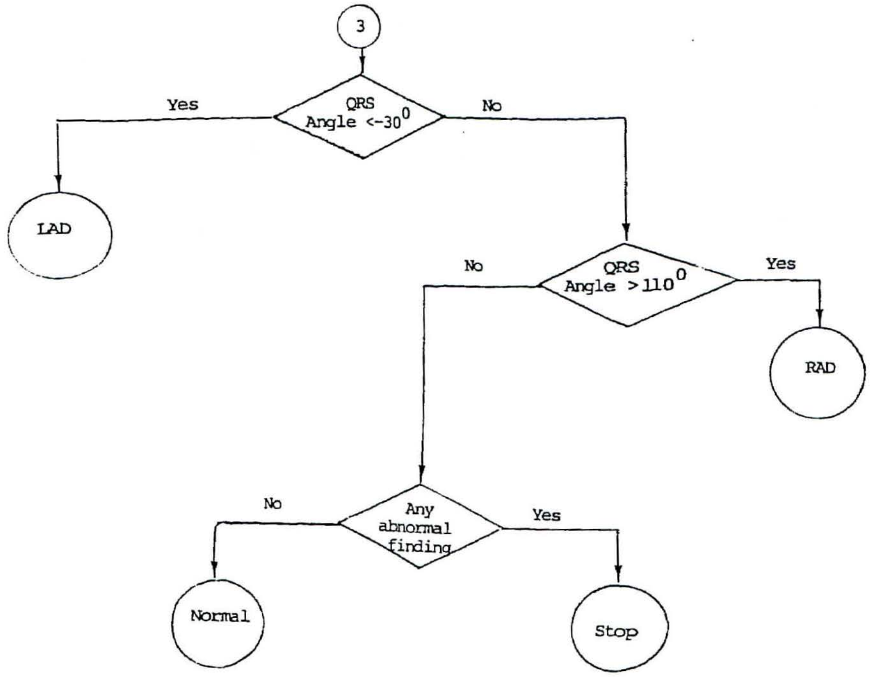


FIG. 2. A logic diagram of the scheme for classifying the QRS complex of the electrocardiogram.



meters used in interpreting the ST and T wave of the electrocardiogram. Again they have been grouped according to their use in the diagnostic logic as outlined below. All of the parameters are calculated on each of the QRS complexes recognized. These parameters are then averaged and the individual parameters from each complex are compared against its average value. That complex whose parameters differ most from the average is thrown out and the remaining complexes are reaveraged in order to achieve the most homogeneous average possible with the data available. It is the average set of parameters which is used to classify the wave.

Figure 2 shows the diagram of the logic flow for the interpretation. The first decision is to determine whether the QRS duration is greater than .12 sec. If this is true the electrocardiogram is checked to determine whether there is a left bundle branch block or right bundle branch block. If there is an RR′ in lead *Z* then the interpretation is right bundle branch block. If there is no R in *Z* and also no S in *X* then the interpretation is left bundle branch block. If, however, the electrocardiogram does not meet one of these two criteria the interpretation of intraventricular conduction defect is made based on the QRS width. If the QRS duration is less than .12 sec. the program checks for an infarction of some type. The first infarction, and by far the most difficult to determine, is that of anterior myocardial infarction. This is done first by determining the S to R ratio in lead Z. This ratio must be greater than 7 before the cardiogram is suspect. If this is true, the ratio is compared against $\frac{1}{10}$ of the minimum S value. If it is greater than this value the electrocardiogram is classified as a probable anterior myocardial infarction and checks are made to further specify it by generating a mid-precordial lead "V_4" as $Z+X$. If the R to S ratio from the derived V4 lead is less than .25 the electrocardiogram is classified as an anterior myocardial infarction. If it is greater, the ratio is compared to $\frac{1}{10}$ of the S to R ratio in lead Z. If it is less, it is classified an anterior myocardial infarction. If this is not true and the S to R ratio in lead Z is greater than 20, the electrocardiogram is reported as having poor R wave progression suggesting anterior myocardial infarction. The reason for making the anterior infarction check a function of the S to R ratio in lead Z is based on the following: In some instances the S to R ratio in Z will be extremely large (i.e., 25–30).However, in many of these cases, as can be seen from the standard 12 lead tracing, the R to S ratio in V4 is approximately normal with a large QS in leads V1, V2, V3. For this reason the requirement for the R to S ratio in the derived V4 in the program would not be near as stringent due to the large ratio in Z and thus would have to be less than perhaps 1 or 2. However, in a case where the S toR ratio in lead Z is not nearly as large perhaps in the order of 8, 9, or 10, in order for there to be evidence of an anterior myocardial infarction, one would expect that there be poor R wave progression or even loss of the R through the precordial leads. This is simulated in the program by making the criteria for the R to S ratio in the derived V4 parameter extremely stringent (.75) indicating a loss of, or at least decrease in, the R wave in this area. Finally the reason for using the probable category in the instance where the R to S ratio in lead Z is greater than 20, and the V4 criteria does not fail is based on the following: there are many small localized anterior infarctions where there is evidence of poor R wave progression through leads V1, V2, V3, indicating a possible anterior infarction, and yet in V5 the ratio is normal. For this reason, through the experience which has been gained with the program, these cases are flagged as poor R wave progression suggesting anterior infarction.

As can be seen from the diagram, once the check for anterior infarction is made, the program checks for inferior infarction and lateral wall infarction by checking the integral or the area under the Q wave in leads Y and leads X. If this shows evidence of a significant Q in lead Y (area less than -500) the program classifies the electrocardiogram as an inferior myocardial pattern. If there is a significant Q in lead X the program then classifies the ECG pattern as compatible with lateral wall infarction. The program next checks for left and right ventricular hypertrophy. Left ventricular hypertrophy depends on the magnitude of the S wave in lead Z and the R wave in lead X. The sum of these two voltages must be greater than 35 mV. The criteria for right ventricular hypertrophy is also based on ratio of the S to R amplitude in lead Z and the R to S ratio in lead X. In both instances this ratio must be less than 1 to indicate right ventricular enlargement. Finally checks are made to determine the axis in the frontal plane using the R or S wave values in leads X and Y. It should be noted at this time, however, that this axis determination in many instances is not compatible with the axis read from the 12 lead standard electrocardiogram. In the case where the computer program indicates a left and right axis deviation, it is subsequently verified on the 12 lead electrocardiogram. The discrepancy, however, occurs in some cases in which the 12 lead electrocardiogram is read as a left or right axis deviation by the cardiologist and this axis deviation is not present in the vector leads. If none of the abnormalities listed above are detected the computer prints "normal QRS complex".

The program next performs the analysis of the ST and T portion. Figure 3 shows a diagram of this logic. The first consideration is a myocardial injury pattern. This is detected by the presence of an ST elevation in leads X, Y or Z greater than .15 mV. If either of these are significant the shape of the ST portion is found to see whether it is concave or convex. If the shape is concave or flat the classification is injury pattern. If there is no evidence of myocardial injury based on these criteria the leads are subsequently analyzed to determine sub-endocardial injury. This is determined by looking for ST depression in leads X or Y of more than .15 mV. If an ST depression is found in either lead the shape of the ST in this lead is then determined. If it is concave the program classifies the pattern as "digitalis effect". If the shape is either a flat or slightly convex the

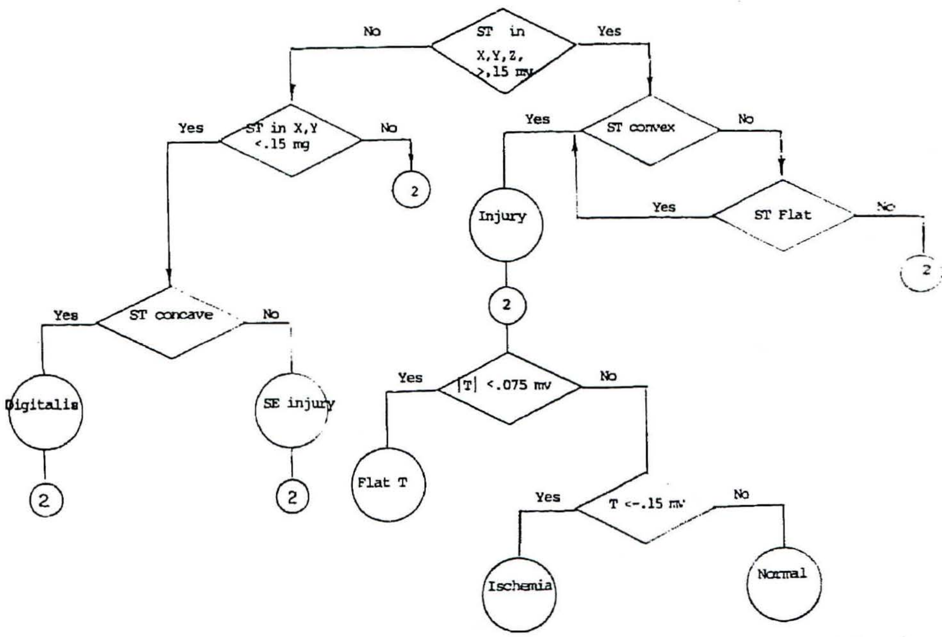


FIG. 3. A scheme for classifying abnormalities in the ST and T wave portion of the electrocardiogram.

program classifies it as "sub-endocardial injury pattern". Next, the T wave is analyzed to determine whether it is upright, inverted or biphasic. A normal T wave is upright. If there is significant T wave inversion in leads X and/or Y the program will indicate "compatable with ischemic pattern". If the absolute value of the voltage is less than .075 mV in leads X and/or Y the program will then report to the Cardiologist that the T wave is flat. No T wave reporting is made on the Z lead alone since upright, flat or inverted T waves on Z are fairly common in normal electrocardiograms. After the T wave is classified the program terminates.

As indicated before, this reporting is done on-line for use at one of the remote terminals. At present there are two ways to get printed reports of the electrocardiographic reading. One is to enter a card through the digital card reader at the central facility at which time a report of the findings are printed out on the line printer. The second method is to request at the termination of any on-line electrocardiogram for a summary result. This will cause the result to be printed out on a teletype at the central facility.

RESULTS

The results of the comparative study of electrocardiograms taken on 287 patients are shown in Figs. 4 and 5. In the QRS analysis (Fig. 4) only two ECG's

Results of ORS analysis

Comp. / Card	N	LVH	RVH	AI	POOR R	II	LI	RBBB	LBBB	IVC	LAD	RAD	UDA	
N	193				2									195
LVH		7												7
RVH			3											3
AI				21										21
POOR R					11									11
II	3					10				1				14
LI							1							1
RBBB	1							8		2				11
LBBB									6	1				7
IVC	1								1					2
LAD	3										8			11
RAD												2		2
UDA													2	2
TOTAL	201	7	3	21	13	10	1	8	7	4	8	2	2	287

FIG. 4. Shows a comparison of the last 287 cases diagnosed by the computer and by the consensus of two or more cardiologists.

RESULTS OF ST-T ANALYSIS

CARD \ COMP.	N	FLAT	IS	DIG	SEIN	INJ	TOTAL
N	190	2	3	2			197
FLAT T	3	26					29
IS	1	2	34				37
DIG	6	1					7
SEIN					9		9
INJ	4					3	7
TOTAL	204	31	37	2	9	3	286

FIG. 5. Compares the results of classification by the computer and by the cardiologist of the ST and T wave portion of the electrocardiogram on 286 cases.

(1% of the electrocardiograms) out of 195 normal cases were mistakenly classified by the computer as abnormal. There were, however, 8 electrocardiograms (9%) classified normal out of 92 read as abnormal by consensus of the cardiologists. Likewise, in the case of the ST and T analysis a lower incidence of false diagnosis of abnormal was found than of false normals. Here 7 electrocardiograms out of 197 were classified abnormal, and 14 abnormals out of 89 were classified normal, giving respective percentages of 4% and 16%. In both analyses there was a greater tendency to call electrocardiograms normal rather than abnormal. This is a result of deliberate emphasis in the program to do just this. Clearly the criteria for judging normal or abnormal in either the QRS or T classification can be adjusted to be either more or less severe. The criteria from this study was set to under-diagnose rather than over-diagnose the abnormal, since this was the desire of the cardiologists using the program.

There are two basic causes for error by the program. The first is in the pattern recognition section where several of the misclassifications occurred as the direct result of not recognizing the onset or end of the QRS wave. This causes an error in either the QRS interpretation or in the ST–T classification. For example, if the end of the QRS is placed too early, the start of the ST portion might be on some part of the S wave, causing the computer to report an ST depression. Improper pattern recognition may also result in a misclassification of the QRS. For example, the one case in which right bundle branch block was misclassified as normal demonstrated an S wave which was flat for an extended length of time and caused the program to mark the end of the QRS prematurely. Hence the program reported a normal width for the QRS.

The second problem involves the criteria for the diagnostic logic. This accounts for most of the errors in the inferior infarction classification where only one criterion was used to make this diagnosis. It is evident from the difficulty encountered in correctly reading cases in this classification that additional criteria should be used as is done in the case of anterior infarction. The results of the ST and T analysis indicate that more work must be done in defining the criteria for these parameters. The major problems here also seem to be the use of only one criterion for judging of these classifications. An investigation is now under way to find additional appropriate criteria. For example, the classification of an injury pattern would not be based on an ST elevation greater than 1.5 mm, but would be based on the amount of elevation relative to the amplitude of the QRS complex. Preliminary investigation using this criterion indicates significant improvement can be anticipated.

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